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Review and prospect of integrated demand response in the multi-energy system ☆

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HIGHLIGHTS

- The concept and the value of integrated demand response are introduced.
- The state-of-the-art research of integrated demand response is reviewed.
- The overviews of the projects on integrated demand response are introduced.
- The key issues on integrated demand response are summarized.

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ABSTRACT

Demand response (DR) is a critical and effective measure to stimulate the demand side resources to interact with renewable generation in the power system. However, the conventional scope of DR cannot fully exploit the interaction capabilities of demand side resources, which limits the energy users in the electric power system. With the revolution of the traditional economic and social pattern based on centralized fossil energy consumption, "*Energy Internet*" is impelling the development of the third industrial revolution, which aims at promoting the incorporation of sustainable energy and internet technology, and facilitating the integration of multi-energy systems (MESs). By integrating electricity, thermal energy, natural gas and other forms of energy, the smart energy hub (SEH) makes it possible for energy users to flexibly switch the source of consumed energy. With the complementarity of MESs, even the inelastic loads can actively participate in DR programs, which fully exploits the interaction capability of DR resources while maintaining the consumers' comfort. This novel vision of the DR programs is termed as "Integrated Demand Response (IDR)". In this context, the state-of-the-art of IDR in the MESs is reviewed for the first time. Firstly, the basic concept of IDR and the value analysis are introduced. The research on IDR in the MES is then summarized. The overviews of the engineering projects around the world are introduced. Finally, the key issues and potential research topics on IDR in the MES are proposed. Hopefully, this paper will provide reference for future research and engineering projects on IDR programs in the MES.

Contents

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1. Introduction

Faced with the serious environmental challenges and energy shortage brought on by the massive consumption of fossil fuels, it has become a global consensus to develop renewable and sustainable energy [1,2]. To solve this worldwide problem, smart grid is actively constructed to facilitate the high penetration of renewable generation [3,4]. However, due to the limited accommodation capability of smart grids, renewable energy curtailment is still a severe issue in existing energy systems. Therefore, the concept of energy internet is emerging at the historic moment [5]. In the book *The Third Industrial Revolution*, Jeremy Rifkin presents that by integrating various forms of energy, the smart grid-centered energy internet will change the conventional energy consumption patterns and stimulate the development of renewable and sustainable energy [6]. In 2015, the Chinese government issued the initiative of *Internet + smart energy*, indicating that the integration of electricity, thermal energy and natural gas is an imperative basis to construct the energy internet [7]. With the rapid development of multi-energy systems and energy internet, the coupling of various forms of energy has been growing tighter along the energy production, delivery and consumption sectors [8].

Demand response is a critical and effective measure to stimulate the demand side resources to interact with renewable generation in the power system [9–11]. According to the reports from Department of Energy (DOE) in the U.S., the electricity users can participate in price-based and incentive-based DR programs [12] to shift or reduce load demands. When the secure operation of the power system is jeopardized or there exist large amounts of renewable energy to be consumed, DR can effectively help keep the balance between electricity supply and demand, and accommodate more renewable energy [13,14]. In most existing research, the DR techniques are applied for a single energy carrier system, e.g. electricity, which are barely feasible when electricity users have some shiftable or curtailable loads [15]. However, inelastic electricity users with only must-run loads cannot participate in any DR program at all. In addition, due to high discomfort costs, most of the electricity users would operate as must-run loads and are reluctant to interrupt or delay their electricity consumption. Therefore, the single energy carrier system cannot fully utilize the demand side resources to implement DR programs.

The core concept of multi-energy systems brings new insights for demand response. The integration of electricity, thermal energy, natural gas and other forms of energy enables all the energy users to be active in DR programs [16]. With the complementarity of MESs, the energy users, including must-run loads, can actively participate in DR programs by converting various forms of energy to electricity in peak periods, instead of purchasing electricity from the power system. From the power system perspective, the energy users reduce electricity demands in peak periods. From the users' point of view, their energy consumption is not changed at all, maintaining consumers' comfort. This idea can be extended to the multi-energy systems, where DR becomes a critical measure to improve the economy and reliability of MESs. This novel vision of DR programs is termed as "Integrated Demand Response". By implementing the IDR programs, the MESs, e.g., district heat/cooling, natural gas, biomass and electric power systems, will backup each other to constitute a more economical and reliable entity. In addition, the response capability of users can be fully exploited without any loss of energy users' comfort.

Up to present, the research on IDR in the MES has been drawing wide attention from the world. In this paper, the review and prospect of IDR in the MES are conducted to provide a reference for the future investigation. Firstly, the basic concept of IDR and the value analysis are introduced. The research on IDR in the MES is then summarized. The overviews of the engineering projects around the world are introduced. Finally, the key issues and potential research topics on IDR in the MES are proposed.

2. Concept of integrated demand response

2.1. The basic concept of IDR

Integrated demand response is a novel vision of DR programs. Taking advantage of the complementarities of different inertia of multi-energy, IDR is aimed at fully exploiting the DR capabilities of all the users and improving the economic and reliable operations of multi-energy systems. The conventional DR programs are merely focused on the electric power sector. Energy users are encouraged to participate in incentive-based and price-based DR programs [17]. When the power system is jeopardized, incentive payments or discounted rates will be broadcast to energy users for pre-contracted load reductions. Or the energy users with some shiftable loads will actively respond to the change of real-time prices (RTPs) and shift load demands away from peak hours to valley hours. These options usually involve a temporary loss of comfort [18–20]. The changes of the electricity consumption behavior cause dissatisfaction and discomfort of energy users. In addition, only a single energy carrier, e.g., electricity, is utilized to implement the DR programs, which may not be applicable for all users. For instance, in power systems, the users with only must-run loads cannot participate in DR programs. Even if some loads are shiftable or curtailable, the DR capability of energy users cannot be fully exploited merely through electricity.

With the development of multi-energy systems, the integration of electricity, thermal energy, natural gas and other forms of energy enables all the energy users to be active in DR programs. The smart energy hub, as the center of converting various kinds of energy, has played an important role in the MES. By co-optimizing and deploying the synergy of MESs, the flexibility and economy of the energy systems will be significantly improved via the strategic complementarity among different forms of energy. Coupling with different energy carriers, SEHs can economically